

## Ultrastructural characteristics of human oocytes vitrified before and after *in vitro* maturation

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**Abstract.** The development of an effective program that combines *in vitro* maturation (IVM) and cryopreservation for immature oocytes would represent a novel advance for *in vitro* fertilization (IVF), especially as a means to preserve the fertility of women in unique situations. The aim of this study was to analyze the ultrastructural characteristics of human oocytes, obtained after controlled ovarian stimulation, to determine whether IVM is best performed before or after vitrification. To this end, we analyzed the following features in a total of 22 MII oocytes: size, zona pellucida and perivitelline space, mitochondria number, M-SER (mitochondria-smooth endoplasmic reticulum) aggregates and M-V (mitochondria-vesicle) complexes, the number of cortical granules and microvilli, and the presence of vacuolization using transmission electron microscopy (TEM). Each oocyte presented a rounded shape, with an intact oolemma, and was surrounded by a continuous zona pellucida and perivitelline space. Statistical analysis comparing oocytes vitrified before or after IVM indicated that there were no significant differences between examined characteristics.

**Key words:** Cryopreservation, Electron microscopy, *In vitro* maturation

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Approximately 80% of oocytes obtained after ovarian cycle stimulation (OS) are in metaphase II (MII). The remaining oocytes, in metaphase I (MI) and prophase I (PI), are usually discarded due to their low capacity for embryonic development [1]. Moreover, there is evidence for an increase in the incidence of aneuploidy in embryos obtained through OS and *in vitro* maturation (IVM) [2], with a clear decrease in successful embryo implantation [3]. If a small number of MII oocytes are obtained, IVM with oocytes in MI or PI can help increase the number of fertilized oocytes and hence the number of embryos that can be transferred to the patient [4]. Additionally, hormonal cycles are unnecessary in order to obtain the immature oocytes, avoiding ovarian hyperstimulation syndrome (OHS) and allowing women with a low response to gonadotropin stimulation to increase their fertility [5]. Moreover, women undergoing oncological treatment can also benefit, as it allows treatment to begin immediately [6]. Consequently, it is important to develop and optimize a protocol that allows PI oocytes to be successfully vitrified and matured via IVM, greatly improving the opportunity to preserve fertility [7]. Therefore, it is crucial to identify any similarities or differences in oocytes matured *in vitro* to establish objective criteria for assessing

oocyte quality and promote research aimed at improving maturation techniques. In this regard, Coticchio *et al.* 2016 [8] have established that most, but not all, oocyte ultrastructural features can develop normally *in vitro*.

On the other hand, mature MII oocytes can be difficult to cryopreserve using current techniques [9] due to certain specific features, such as a relatively large volume. This leads to a low surface-to-volume ratio, high water content, a high degree of cytoplasmic specialization (including cytoskeletal characteristics), and precise chromosomal arrangement [10]. In fact, ultrastructural damage is one of the main adverse effects associated with cryopreservation due to the toxic effects of cryoprotectants, the formation of ice crystals, and osmotic stress [11]. The meiotic spindle is especially sensitive to the cryopreservation process. Cryopreservation of immature PI oocytes could avoid some of these issues, especially those related to spindle and chromosome cryodamage, as they are protected by the nuclear membrane. However, PI oocytes still need to be matured *in vitro* [12] but current protocols for oocyte cryopreservation and maturation are suboptimal and clinical success has only been obtained in a limited number of cases [13]. It is therefore essential to define some objective criteria to establish how oocyte quality may be affected by cryopreservation, with a view to supporting or ruling out the applicability of different protocols and assessing the possible health risks for children born from cryopreserved oocytes [14].

During oocyte maturation, we can distinguish between two distinct processes, nuclear maturation and cytoplasmic maturation. In the nuclear maturation phase, meiotic processes restart, going from PI to MII. Cytoplasmic maturation includes changes to the ooplasm that are

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necessary for the oocyte's future development [15]. Synchronization of these two processes ensures normal fertilization and successful embryonic development [16]. Transmission electron microscopy (TEM) is a valuable research tool that can be used to determine an oocyte's cytoplasmic maturation status. Within oocytes, the most abundant organelles are mitochondria. These often associate with the membrane of the smooth endoplasmic reticulum (SER) or small vesicles and these associations play an important role in the production of useful substances during fertilization and in membrane neoformation during early embryogenesis [17]. They may also act to regulate free calcium levels and ATP production, and have a role in several cellular activities at fertilization, including calcium signal mediation [18]. Mitochondria-smooth endoplasmic reticulum (M-SER) aggregates are very abundant in MII oocytes and are considered a marker for normal cytoplasmic maturation. In contrast, high numbers of mitochondria-vesicle (M-V) complexes are an indicator of cellular aging due to exceeding the IVM time. This can adversely affect fertilization and the early stages of embryonic development [19]. It is also necessary to analyze the arrangement of cortical granules and the degree of vacuolization [18].

Assessing oocyte quality is based on many morphometric criteria. In order to evaluate both structural and ultrastructural oocyte characteristics, several parameters should be assessed using both light microscopy (LM) and TEM [20]. These include oocyte shape and dimension, zona pellucida (ZP) texture, perivitelline space (PVS) appearance, oolemma integrity and density, mitochondria, M-SER aggregate and M-V complex number, quantity of cortical granules (CG) and their arrangement [10], and the presence of ooplasmic vacuolization [21].

The aim of the present study was to evaluate ultrastructure oocyte characteristics in order to determine whether IVM should be performed before or after vitrification, as little is known about the efficiency or consequences of cryopreservation in immature and *in vitro* matured oocytes.

## Materials and Methods

This study was reviewed and accepted by the Ethical and Scientific Committee of the La Fe Hospital, Valencia, Spain. Signed informed consent was obtained from all participants.

### Oocyte collection

Controlled ovarian stimulation of patients was performed with a short antagonist protocol using (150–300 IU/day) rec-FSH (Gonal F 1050; Merck and Co, Madrid, Spain) and GnRH (Orgalutran®; MSD and Co, Hoddesdon, UK) for pituitary suppression. Triggering was performed through the administration of 250 mcg of rec-hCG (Ovitrelle, Merck, London, UK) when there were at least three follicles > 16 mm present. Oocyte retrieval was performed via vaginal puncture guided by ultrasound 36 h later. Cumulus-oocyte complexes were removed using hyaluronidase (SynVibro® Hyadase; Origio®, Måløv, Denmark) solution for a maximum of 30 sec with a denuding pipette (Flexipet® Denuding Pipette, Cook® Medical, Bloomington, IN, USA). In total, 22 MII immature oocytes were identified through the presence of a germinal vesicle (PI stage) and included in this study. Of these, 10 were vitrified before IVM (group

1) and 12 were vitrified after IVM (group 2).

### *In vitro* maturation

Healthy oocytes were placed in an IVM medium consisting of blastocyst medium (CCM™, Vitrolife®, Göteborg, Sweden) supplemented with human menopausal gonadotropin (hMG, Menopur® 75 U.I., Ferring®, Madrid, Spain) and serum substitute (SSS, IrvineScientific®, Santa Ana, CA, USA) under paraffin oil at 37°C in a 6% CO<sub>2</sub> humidified atmosphere. After 24 and 48 h of culture, mature oocytes were identified by the presence of the first polar body using an inverted microscope (Olympus, IX70, Tokyo, Japan). The general distribution of cytoplasmic organelles during oocyte maturation is shown in Fig. 1.

### Oocyte vitrification

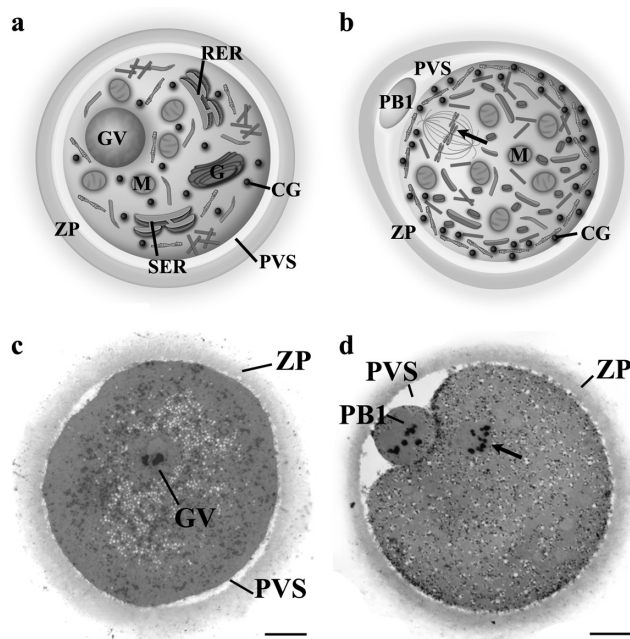
Oocytes (PI and MII) were vitrified in Kitazato® (KITAZATO Vitrification/Thawing media, Biopharma, Shizuoka, Japan) medium using the Cryotop® system (KITAZATO Vitrification/Thawing media), according to a modified drop protocol proposed by Wang *et al.* 2013 [22]. Oocytes were equilibrated in a 20 µl drop of basic solution (BS) for 1 min before the drop was merged with a 20 µl drop of equilibration solution (ES) for 3 min. Next, a second 20 µl drop of ES was merged for a further 3 min. The oocytes were then placed in a new 20 µl drop of ES for 6 min. After equilibration, the oocytes were transferred to four drops of vitrification solution (VS) and loaded into the Cryotop® to be stored in liquid nitrogen. The total time for the final process was 60 sec. All procedures were performed at room temperature (22–25°C).

Oocyte warming was performed based on procedures specific to the Kitazato® Kit. Each Cryotop® was removed from liquid nitrogen and quickly submerged in 1 ml of thawing solution (TS) at 37°C for 1 min. The oocytes were then transferred to 300 µl of dilution solution (DS) for 3 min and then transferred to 300 µl of washing solution (WS). After 5 min, the oocytes were washed in new WS medium and placed in IVM medium. These procedures were performed at room temperature (22–25°C).

The survival rate after thawing was evaluated microscopically 2 to 3 h after culture and was based on observations of the morphology and integrity of the oocyte membrane.

### Electron microscopy

The oocytes were fixed and processed for TEM analysis using methods previously described by Nottola *et al.*, 2007 [23]. Oocyte fixation was performed using 2% glutaraldehyde (SIC, Rome, Italy) in phosphate buffered saline (PBS). After fixation for at least 2 days at 4°C, samples were rinsed in PBS, postfixed with 1% osmium tetroxide (Electron Microscopy Sciences, Hatfield, PA, USA) in PBS and rinsed again in PBS. The oocytes were then embedded in small blocks of 2% agar (Sigma-Aldrich, St. Louis, MO, USA) approximately 5 × 5 × 1 mm in size. These were then dehydrated in an ascending series of ethanol concentrations, immersed in propylene oxide (Electron Microscopy Sciences, Hatfield, PA, USA) for solvent substitution, and finally embedded in epoxy resin EPON-812 (Electron Microscopy Sciences, Hatfield, PA, USA). Semithin sections of 1.0 µm thickness were cut serially with a glass knife on a Leica LKB-III ultramicrotome and then mounted on gelatinized slides, stained



**Fig. 1.** General distribution of cytoplasmic organelles during human oocyte maturation. Diagram of PI oocytes (a) Diagram of metaphase-II oocytes, (b) Micrographs of PI, (c) and metaphase-II (d) shown by LM. GV = germinal vesicle, ZP = zona pellucida; PVS = perivitelline space, PB1 = 1<sup>st</sup> polar body; M = mitochondria; G = Golgi apparatus; CG = cortical granules; RER = rough endoplasmic reticulum; SER = smooth endoplasmic reticulum. Note the metaphase II oocyte with chromosomes at the equator (arrow), cortical granules disposed beneath the oolemma, mitochondria uniformly distributed throughout the cytoplasm, fragmented Golgi apparatus, and reorganization of the cytoskeleton (modified from Mao *et al.*, 2014 [32]). Bar: 20  $\mu$ m (c, d).

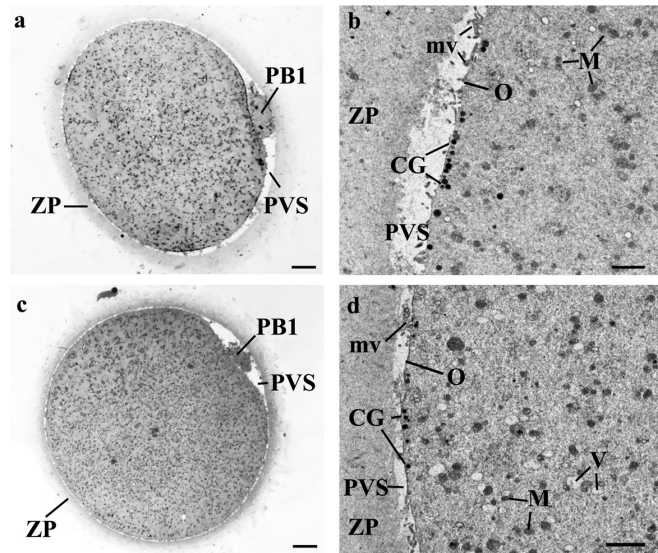
with 0.5% toluidine blue, and examined under a Leica DMRB light microscope. Photomicrographs were taken with a Lumenera Infinity microscope camera (Microsercon, SLU, Madrid, Spain). Ultrathin sections were cut with a diamond knife and double-contrasted with uranyl acetate 5% and lead citrate 2.5%. These were examined under a JEOL JEM-1400 Plus transmission electron microscope equipped with a Gatan Orius digital camera (Gatan, Pleasanton, CA, USA) for image capture.

#### Morphometric analysis

In this study, only oocytes that were visually ascertained to be of good quality using LM were selected for ultrastructural analysis. Features used to evaluate quality included the presence of a regular and rounded shape, a clear and moderately granular cytoplasm, a narrow PVS with the first polar body, and an intact and colorless ZP.

The evaluation of organelle density was performed through the collection of TEM micrographs of whole surface profiles at 6300 $\times$  magnification on three equatorial ultra-thin sections per oocyte (distance between the sections was 3–4  $\mu$ m). These images were digitally enlarged to aid identification of organelles.

ImageJ software [24] was used to measure the dimensions of



**Fig. 2.** Light and electron micrographs of human oocytes vitrified before (group 1) and after (group 2) *in vitro* maturation. Group 1 (a, b) and group 2 (c, d). Continuous zona pellucida (ZP) and perivitelline space (PVS) can be observed (a–d). Note the regular presence of microvilli (mv) (b, d). A row of electron-dense cortical granules (CG) is seen under the oolemma (O) (b, d). M = Mitochondria, V = vesicle, PB1 = 1<sup>st</sup> polar body. Bar: 10  $\mu$ m (a, c); 2  $\mu$ m (b, d).

mitochondria, CG, microvilli, and vesicles. For each experimental group, at least six oocytes were selected for statistical analysis.

#### Statistical analysis

All data were expressed as a mean  $\pm$  standard deviation and compared using unpaired t-tests (R software v3.3.1, <https://www.r-project.org/>). Differences in values were considered significant if  $P < 0.05$ . Mitochondria and vesicle values were expressed as the number of each per 100  $\mu$ m<sup>2</sup>, while CG and microvilli values were expressed as the number per 10  $\mu$ m of the linear surface profile.

## Results

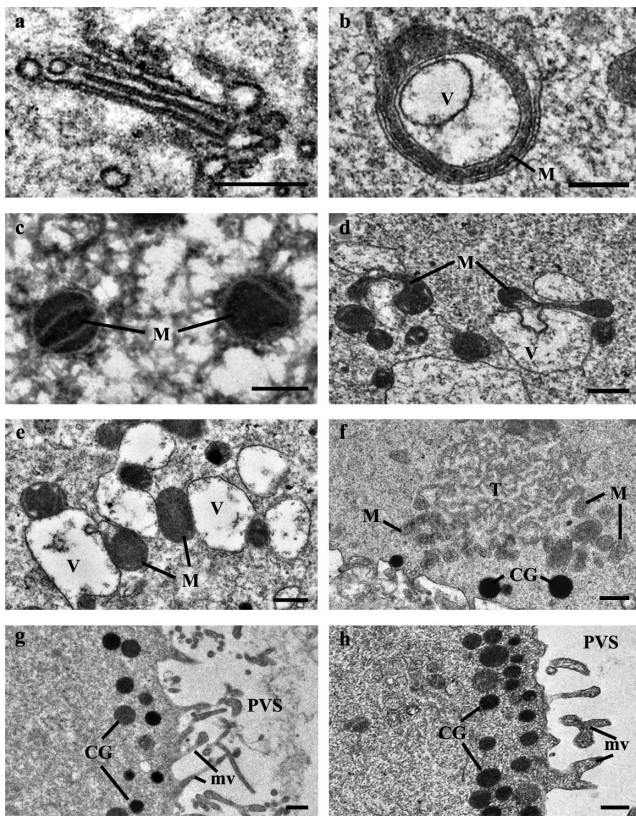
#### General features

Through LM examination of semithin sections, both groups (oocytes vitrified before and after IVM) possessed good quality oocytes, as evidenced by their regular rounded shape, a maximum diameter of 90–105  $\mu$ m, the cytoplasm showing a uniform and fine granular texture, and were surrounded by a continuous ZP and PVS (Figs. 2a and 2c). TEM analysis at low magnification (Figs. 2b and 2d) revealed that organelles in both groups were abundant and uniformly dispersed in the homogeneous ooplasm, with slight microvacuolization of the cytoplasm. However, some Golgi apparatus were occasionally observed in oocytes vitrified before IVM (Fig. 3a).

#### Mitochondria

Ultrastructural analysis using TEM revealed that the most numerous and commonly identified organelles were mitochondria. These often associated with the SER to form large M-SER aggregates or, less





**Fig. 3.** Microphotograph of different organelles found in human oocytes vitrified before (group 1) (a, c, e, g) and after *in vitro* maturation (group 2) (b, d, f, h). a) Golgi apparatus. b) Some SER small vesicles (V) are encircled by flattened, crescent-shaped mitochondria (M). c) Rounded mitochondria endowed with few transversal cristae. d-e) M-V complexes. Note elongated forms with a central constriction. f) M-SER aggregates. g, h) Cortical granules (CG) disposed just beneath the oolemma. SER = smooth endoplasmic reticulum; T = aggregates of tubules; mv = microvilli; PVS = perivitelline space. Bar: 250 nm (a-c); 500 nm (d-h).

frequently, associated with small vesicles (V) to form M-V complexes (Figs. 3b–3e). Mitochondria were localized homogeneously across the entire cytoplasm and were rounded or oval in profile, with few transversal cristae and a matrix showing moderate electrodensity (Fig. 3c). We also found elongated mitochondrial forms confined to the center of the ooplasm (Fig. 3d). Large M-SER aggregates were located in the cortical areas of the ooplasm (Fig. 3f). The number of mitochondria was slightly higher in group 2. The mean number  $\pm$  SD of mitochondria per 100  $\mu\text{m}^2$  was  $45.6 \pm 7.5$  and  $54.33 \pm 8.6$  in oocytes vitrified before and after IVM, respectively. However, there was no statistically significant difference in the number of mitochondria among groups ( $P = 0.119$ ) (Fig. 4a).

### Vesicles

In all observed oocytes, typical numbers of SER vesicles and complexed M-V were present. The mean number  $\pm$  SD of vesicles per 100  $\mu\text{m}^2$  was found to be  $6.69 \pm 3.1$  and  $7.25 \pm 1.8$  in oocytes

vitrified before and after IVM, respectively. There was no significant difference among groups ( $P = 0.930$ ) (Fig. 4b).

### Cortical granules

Using electron microscopy, we were able to identify up to three rows of spherical CG immediately below the oolemma through electron-dense matrix differences (Figs. 3g and 3h). However, a few isolated CG were occasionally detected in the inner ooplasm of some oocytes in group 1 (oocytes vitrified before IVM). Morphometric analysis revealed that the mean number  $\pm$  SD of cortical granules per 10  $\mu\text{m}$  of the linear surface profile was  $5.68 \pm 2.5$  and  $8.99 \pm 3.1$  in oocytes vitrified before and after IVM respectively, and there was no significant difference ( $P = 0.3535$ ) (Fig. 4c).

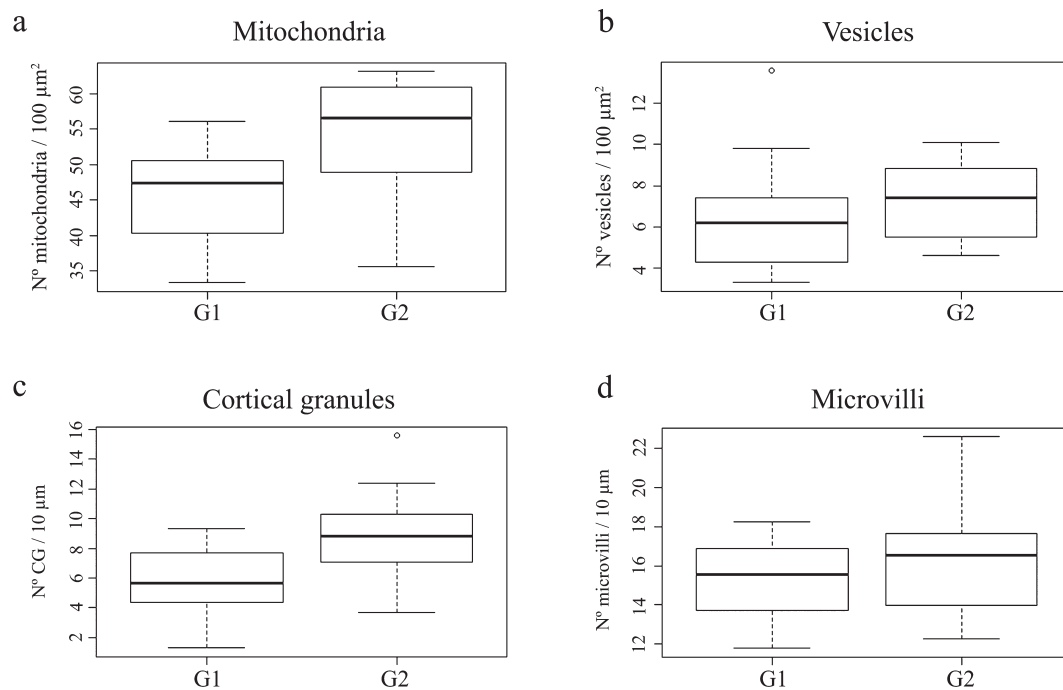
### Microvilli

Similar ultrastructural features were found in both groups. Oocytes were surrounded by a regular oolemma, with numerous microvilli arranged in a typical pattern projecting into a PVS (Figs. 3g and 3h). There was no significant difference in the number of microvilli per 10  $\mu\text{m}$  of the linear surface profile between the two groups (mean number  $\pm$  SD:  $15.16 \pm 2.2$  and  $16.21 \pm 2.9$  in oocytes vitrified before and after IVM, respectively,  $P = 0.8361$ ) (Fig. 4d).

## Discussion

In recent years, the recovery of immature oocytes and subsequent IVM has been found to be an attractive alternative to *in vitro* fertilization (IVF) [25]. Although IVM methods are not yet fully optimized for humans [26], there are recent reports of healthy infants being born following IVM [27, 28]. However, little research has been carried out into whether IVM should be performed before or after vitrification. Zhang *et al.* 2011 [29] have suggested that vitrification of immature oocytes may be a better way to preserve microtubule organization and reduce cytoskeletal spindle damage. On the other hand, other studies [30, 31] report that the IVM procedure is more efficient when it is performed before oocyte vitrification. In the present work, we have investigated the ultrastructural changes that occur in the cytoplasmic organelles of oocytes in both cases.

Cytoplasmic maturation is a complex process, but electron microscopy allows oocyte quality to be assessed based on morphometric criteria. The criteria used for the identification of cytoplasm immaturity are the presence of numerous CG dispersed in the oocyte cortex instead of being positioned beneath the oolemma, the presence of Golgi complexes still forming cortical vesicles, the absence of mitochondria in the oocyte cortex, the absence of SER tubule aggregates, and the presence of SER large vesicles without associated mitochondria. Our analysis confirmed that all oocytes in our study could be considered good quality when assessed by LM and TEM. In both groups, oocytes were round in shape and the oolemma, ZP, and PVS appeared continuous. In fact, CG were found in similar numbers beneath the oolemma, with only a few isolated CG located in the subcortex of oocytes in group 1 (oocytes vitrified before IVM). Moreover, CG showed variation in electrodensity, which represents an important parameter to evaluate cytoplasm maturation. Sparsely electrodense CG can be interpreted as immature organelles or as an early morphological sign of exocytosis [14, 23]. However, low



**Fig. 4.** G1: Oocytes vitrified before IVM. G2: Oocytes vitrified after IVM. The graphs represent the number of cytoplasmic organelles, number of mitochondria per 100  $\mu\text{m}^2$  (a), number of vesicles per 100  $\mu\text{m}^2$ , (b) number of cortical granules per 10  $\mu\text{m}$  linear surface profile, (c) and number of microvilli per 10  $\mu\text{m}$  linear surface profile (d). Values for each group are expressed as mean  $\pm$  SD. No statistical differences were found between the two groups.

levels of vacuolization have also been observed, which could be considered a marker of high quality oocytes [32].

In a small number of oocytes vitrified before IVM, some Golgi complexes were observed. Previous studies [33] have reported that Golgi apparatus are rarely found in MII oocytes. This may suggest that oocytes vitrified before IVM are of a lower quality than those vitrified afterwards. However, this could also be interpreted as an increase in protein production in the ooplasm.

The number and status of mitochondria were also similar between both groups, with a comparable number, shape, internal architecture, and texture. The mitochondria showed no signs of apoptosis, as reported in other studies that have examined IVM of oocytes [29]. Mitochondria, M-SER aggregates, and M-V complexes play a role in the production of materials useful for maturation and fertilization [34]. Mitochondrial abnormalities may also be associated with embryo incompetence [35, 36]. Our results have shown that the mitochondria in both groups did not have a disorganized matrix or the presence of dark vesicles.

With regards to vesicles, SER elements may dynamically acquire different shapes (tubules or vesicles), although they belong to the same system of interconnected membranes [21]. In this respect, during the maturation of the oocyte, the aggregation of SER tubules appears to be the earliest observable event. Subsequently, these tubules become surrounded by mitochondria, forming mitochondria-SER aggregates. Moreover, small M-V complexes are found in both immature and mature oocytes [12, 37].

Finally, the ultrastructure of the microvilli showed a normal pattern

in both groups. This characteristic is very important as improper microvilli distribution contributes to fertilization failure through ineffective spermatozoon-oocyte fusion [38].

In conclusion, human oocytes can be vitrified before or after IVM, but oocytes cryopreserved after IVM show slight improvements in terms of the ultrastructural characteristics of cytoplasm maturation. However, further studies are needed to confirm these results owing to the limited number of samples used.

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### References

1. Shu Y, Gebhardt J, Watt J, Lyon J, Dasig D, Behr B. Fertilization, embryo development, and clinical outcome of immature oocytes from stimulated intracytoplasmic sperm injection cycles. *Fertil Steril* 2007; **87**: 1022–1027. [Medline] [CrossRef]
2. Escribá L, Grau N, Mercader A, Rubio C, Pellicer A, Escribá MJ. Spontaneous in vitro maturation and artificial activation of human germinal vesicle oocytes recovered from stimulated cycles. *J Assist Reprod Gener* 2011; **28**: 111–117. [Medline] [CrossRef]
3. Fasano G, Moffa F, Dechène J, Englert Y, Demeestere I. Vitrification of in vitro matured oocytes collected from antral follicles at the time of ovarian tissue cryopreservation. *Reprod Biol Endocrinol* 2011; **9**: 150–154. [Medline] [CrossRef]
4. Tan SL, Child TJ. In-vitro maturation of oocytes from unstimulated polycystic ovaries. *Reprod Biomed Online* 2002; **4**(Suppl 1): 18–23. [Medline] [CrossRef]

5. Barton SE, Missmer SA, Berry KE, Ginsburg ES. Female cancer survivors are low responders and have reduced success compared with other patients undergoing assisted reproductive technologies. *Fertil Steril* 2012; **97**: 381–386. [Medline] [CrossRef]
6. Gulekli B, Kovali M, Aydinler F, Dogan S, Dogan SS. IVM is an alternative for patients with PCO after failed conventional IVF attempt. *J Assist Reprod Genet* 2011; **28**: 495–499. [Medline] [CrossRef]
7. Fadini R, Mignini Renzini M, Dal Canto M, Epis A, Crippa M, Calari I, Brigante C, Coticchio G. Oocyte in vitro maturation in normo-ovulatory women. *Fertil Steril* 2013; **99**: 1162–1169. [Medline] [CrossRef]
8. Coticchio G, Dal Canto M, Fadini R, Mignini Renzini M, Guglielmo MC, Miglietta S, Palmerini MG, Macchiarelli G, Nottola SA. Ultrastructure of human oocytes after in vitro maturation. *Mol Hum Reprod* 2016; **22**: 110–118. [Medline] [CrossRef]
9. Hosseini SM, Nasr-Esfahani MH. What does the cryopreserved oocyte look like? A fresh look at the characteristic oocyte features following cryopreservation. *Reprod Biomed Online* 2016; **32**: 377–387. [Medline] [CrossRef]
10. Khalili MA, Maione M, Palmerini MG, Bianchi S, Macchiarelli G, Nottola SA. Ultrastructure of human mature oocytes after vitrification. *Eur J Histochem* 2012; **56**: e38. [Medline] [CrossRef]
11. Nottola SA, Albani E, Coticchio G, Palmerini MG, Lorenzo C, Scaravelli G, Borini A, Levi-Setti PE, Macchiarelli G. Freeze/thaw stress induces organelle remodeling and membrane recycling in cryopreserved human mature oocytes. *J Assist Reprod Genet* 2016; **33**: 1559–1570. [Medline] [CrossRef]
12. Palmerini MG, Antinori M, Maione M, Cerusico F, Versaci C, Nottola SA, Macchiarelli G, Khalili MA, Antinori S. Ultrastructure of immature and mature human oocytes after cryotop vitrification. *J Reprod Dev* 2014; **60**: 411–420. [Medline] [CrossRef]
13. Nottola SA, Camboni A, Van Langendonck A, Demylle D, Macchiarelli G, Dolmans MM, Martinez-Madrid B, Correr S, Donne J. Cryopreservation and xenotransplantation of human ovarian tissue: an ultrastructural study. *Fertil Steril* 2008; **90**: 23–32. [Medline] [CrossRef]
14. Coticchio G, Borini A, Distratis V, Maione M, Scaravelli G, Bianchi V, Macchiarelli G, Nottola SA. Qualitative and morphometric analysis of the ultrastructure of human oocytes cryopreserved by two alternative slow cooling protocols. *J Assist Reprod Genet* 2010; **27**: 131–140. [Medline] [CrossRef]
15. Lin Y-H, Hwang J-L. In vitro maturation of human oocytes. *Taiwan J Obstet Gynecol* 2006; **45**: 95–99. [Medline] [CrossRef]
16. Liu S, Li Y, Feng HL, Yan JH, Li M, Ma SY, Chen ZJ. Dynamic modulation of cytoskeleton during in vitro maturation in human oocytes. *Am J Obstet Gynecol* 2010; **203**: 151.e1–151.e7. [Medline] [CrossRef]
17. Motta PM, Nottola SA, Familiari G, Makabe S, Stallone T, Macchiarelli G. Morphodynamics of the follicular-luteal complex during early ovarian development and reproductive life. *Int Rev Cytol* 2003; **223**: 177–288. [Medline] [CrossRef]
18. Bianchi S, Macchiarelli G, Micara G, Linari A, Boninsegna C, Aragona C, Rossi G, Cecconi S, Nottola SA. Ultrastructural markers of quality are impaired in human metaphase II aged oocytes: a comparison between reproductive and in vitro aging. *J Assist Reprod Genet* 2015; **32**: 1343–1358. [Medline] [CrossRef]
19. Miao Y-L, Kikuchi K, Sun Q-Y, Schatten H. Oocyte aging: cellular and molecular changes, developmental potential and reversal possibility. *Hum Reprod Update* 2009; **15**: 573–585. [Medline] [CrossRef]
20. Nottola SA, Macchiarelli G. Structural bases of the ovarian function: an introduction. *Microsc Res Tech* 2006; **69**: 384–385. [Medline] [CrossRef]
21. Bianchi V, Macchiarelli G, Borini A, Lappi M, Cecconi S, Miglietta S, Familiari G, Nottola SA. Fine morphological assessment of quality of human mature oocytes after slow freezing or vitrification with a closed device: a comparative analysis. *Reprod Biol Endocrinol* 2014; **12**: 110. [Medline] [CrossRef]
22. Wang CT, Liang L, Witz C, Williams D, Griffith J, Skorupski J, Haddad G, Gill J, Wang W. Optimized protocol for cryopreservation of human eggs improves developmental competence and implantation of resulting embryos. *J Ovarian Res* 2013; **6**: 15. [Medline] [CrossRef]
23. Nottola SA, Macchiarelli G, Coticchio G, Bianchi S, Cecconi S, De Santis L, Scaravelli G, Flamigni C, Borini A. Ultrastructure of human mature oocytes after slow cooling cryopreservation using different sucrose concentrations. *Hum Reprod* 2007; **22**: 1123–1133. [Medline] [CrossRef]
24. Schindelin J, Arganda-Carreras I, Frise E, Kaynig V, Longair M, Pietzsch T, Preibisch S, Rueden C, Saalfeld S, Schmid B, Tinevez JY, White DJ, Hartenstein V, Eliceiri K, Tomancak P, Cardona A. Fiji: an open-source platform for biological-image analysis. *Nat Methods* 2012; **9**: 676–682. [Medline] [CrossRef]
25. Khalili MA, A Nottola S, Shahedi A, Macchiarelli G. Contribution of human oocyte architecture to success of in vitro maturation technology. *Iran J Reprod Med* 2013; **11**: 1–10. [Medline]
26. Shahedi A, Hosseini A, Khalili MA, Norouzi M, Salehi M, Piriaei A, Nottola SA. The effect of vitrification on ultrastructure of human in vitro matured germinal vesicle oocytes. *Eur J Obstet Gynecol Reprod Biol* 2013; **167**: 69–75. [Medline] [CrossRef]
27. Donnez J, Silber S, Andersen CY, Demeestere I, Piver P, Meirow D, Pellicer A, Dolmans MM. Children born after autotransplantation of cryopreserved ovarian tissue: a review of 13 live births. *Ann Med* 2011; **43**: 437–450. [Medline] [CrossRef]
28. Urquiza MF, Carretero I, Cano Carabajal PR, Pasqualini RA, Felici MM, Pasqualini RS, Quintans CJ. Successful live birth from oocytes after more than 14 years of cryopreservation. *J Assist Reprod Genet* 2014; **31**: 1553–1555. [Medline] [CrossRef]
29. Yang YJ, Zhang YJ, Li Y. Ultrastructure of human oocytes of different maturity stages and the alteration during in vitro maturation. *Fertil Steril* 2009; **92**: 396.e1–396.e6. [Medline] [CrossRef]
30. Versieren K, Heindryckx B, OLeary T, De Croo I, Van den Abbeel E, Gerris J, De Sutter P. Slow controlled-rate freezing of human in vitro matured oocytes: effects on maturation rate and kinetics and parthenogenetic activation. *Fertil Steril* 2011; **96**: 624–628. [Medline] [CrossRef]
31. Fasano G, Demeestere I, Englert Y. In-vitro maturation of human oocytes: before or after vitrification? *J Assist Reprod Genet* 2012; **29**: 507–512. [Medline] [CrossRef]
32. Nottola SA, Coticchio G, Sciajno R, Gambardella A, Maione M, Scaravelli G, Bianchi S, Macchiarelli G, Borini A. Ultrastructural markers of quality in human mature oocytes vitrified using cryoleaf and cryoloop. *Reprod Biomed Online* 2009; **19**(Suppl 3): 17–27. [Medline] [CrossRef]
33. Mao L, Lou H, Lou Y, Wang N, Jin F. Behaviour of cytoplasmic organelles and cytoskeleton during oocyte maturation. *Reprod Biomed Online* 2014; **28**: 284–299. [Medline] [CrossRef]
34. Shahedi A, Khalili MA, Soleimani M, Morshedizad S. Ultrastructure of in vitro matured human oocytes. *Iran Red Crescent Med J* 2013; **15**: e7379. [Medline] [CrossRef]
35. Motta PM, Nottola SA, Makabe S, Heyn R. Mitochondrial morphology in human fetal and adult female germ cells. *Hum Reprod* 2000; **15**(Suppl 2): 129–147. [Medline] [CrossRef]
36. Van Blerkom J. Mitochondria in human oogenesis and preimplantation embryogenesis: engines of metabolism, ionic regulation and developmental competence. *Reproduction* 2004; **128**: 269–280. [Medline] [CrossRef]
37. El Shafie M, Sousa M, Kruger TF. An Atlas of the Ultrastructure of Human Oocytes. New York, USA, 2000.
38. Swain JE, Pool TB. ART failure: oocyte contributions to unsuccessful fertilization. *Hum Reprod Update* 2008; **14**: 431–446. [Medline] [CrossRef]